Technical Review of Methods to Enhance Biological Degradation in Sanitary Landfills

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Biological processes are known to reduce the organic fraction of municipal solid waste, but current landfilling practices have not been altered to reflect this knowledge. The advantages of enhancing degradation of solid waste are as follows: reduced period of leachate treatment, increased methane production, expedited landfill site reclamation through stabilized waste mining, and accelerated subsidence permitting recovery of valuable landfill air space. The techniques that can be used to enhance biological degradation include leachate recirculation, addition of nutrients, shredding, sludge addition, lift design, temperature and moisture content management. Manipulation of these variables promotes a more conducive environment for microbial activity. Research on landfill management strategies through laboratory and full-scale studies has shown the validity of applying the enhancement techniques with regards to reducing leachate strength and increasing methane production. These practices focus on the use of landfills as bioreactors, which enables long-term flexibility and assures compliance with future regulations and discharge standards.

Key words: landfill leachate, recirculation, biological degradation of solid waste

Introduction

Major concerns regarding the impact of municipal landfills on the environment are related to leachate quantity and quality, gas generation, and decomposition processes occurring in the landfill. The main processes responsible for the degradation of solid waste in the landfill are biological processes. It is desirable to minimize the time period in which degradation occurs in order to reduce gas emissions after the landfill is closed, to ease the requirements of leachate treatment, and to be successful in reclaiming the landfill site.

Leachate that has a high concentration of organic compounds requires a greater amount of oxygen during aerobic treatment, leading to higher energy costs. By enhancing biological degradation processes, the period in which the leachate is highly polluted decreases. The peak organic concentration of the leachate is also lessened, which results in reducing the leachate treatment demand. Landfill gas production can lead to efficient recovery of energy from the landfill. High methane concentrations in the landfill gas are important for efficient energy conversion. When gas
production rates are accelerated, energy recovery processes can begin at an earlier stage and can be decomposed after closure of the landfill.

Several possible enhancement techniques can be implemented to increase biological activity in landfills. These techniques include leachate recycling, use of buffers and/or nutrients, sludge addition, reduction of waste particle size, waste lift design, and moisture content management.

Despite knowledge of benefits of biological enhancement techniques, there have been few changes in recent years in sanitary landfill construction and operation techniques. This paper reviews the current state-of-the-art in landfill leachate management strategies involved in both laboratory and full-scale studies. As a result, it reveals the validity of applying various enhancement techniques for degradation of solid waste in sanitary landfills.

**Biochemical Process in Landfills**

The benefits of enhancing biological degradation in sanitary landfills are only possible upon understanding the basic biochemical processes that occur in such environment. Stabilization of waste in a municipal solid waste (MSW) landfill is dominated by microbial activity which governs the composition of leachate and the generation of landfill gas. Concentration of organic substances in a landfill and the age of the landfill are the other two factors controlling MSW stabilization (Chiampo et al. 1996; Nozhevnikova et al. 1993). The most important stabilization process is the anaerobic decomposition, as the availability of oxygen as a terminal electron acceptor is limited in the sealed landfill (Qian and Barlaz 1996; Watson-Craik et al. 1995; Senior 1992).

**Solid Waste Degradation Sequence**

The sequence of waste decomposition begins with a relatively short aerobic degradation phase, which occurs directly after the waste has been deposited in the landfill; it is followed by a long anaerobic degradation phase. Methane gas and carbon dioxide are the main products of the stabilization process. Several researchers (Buckley and Lowery 1996; Braber 1995; Al-Yousifi and Pohland 1993; Byrom, 1993; Barlaz et al. 1989a; Pohland 1980) presented an idealized sequence of the processes involved in the decomposition of waste and the consequence on the landfill gas and leachate composition during the various phases of waste decomposition. Each stage of waste decomposition is characterized by its own set of physical, chemical and microbial activities (Reinhart and Al-Yousifi 1996; Christensen and Kjeldsen 1989; Pohland 1980). Major bacterial groups involved in this decomposition process include fermentative bacteria, acetogenic bacteria, methanogenic bacteria and sulphate-reducing bacteria.

Phase I involves a short period of aerobic decomposition in which easily degradable organic matter is consumed and carbon dioxide is generated. In an aerobic environment, a large number of interactions among species are
responsible for biodegradation. A community of microorganisms works in "syntrophy", where one group of organisms produces metabolites which are then usable by other members of the group (Senior 1992).

Phase II is the first intermediate anaerobic decomposition phase and occurs immediately after the aerobic phase. The first stage consists of the fermentative bacteria, which are a large heterogeneous group of facultatively anaerobic microorganisms. The fermenters hydrolyze and ferment solid and complex dissolved organic compounds into primarily volatile acids, alcohols, hydrogen and carbon dioxide. The acetogenic bacteria function in the second decomposition phase and are also a large heterogenic group. These bacteria convert the products generated by the fermenters to acetic acid, hydrogen and carbon dioxide.

During this second phase the leachate is acidic with a pH of less than 6.5, and may contain high concentrations of fatty acids, calcium, iron, heavy metals and ammonia (Ejlertsson et al. 1996; Doedens and Cord-Landwehr 1989). The presence of ammonia is mainly due to the hydrolysis and fermentation of protein compounds. Nitrogen in the gas phase is reduced as a result of carbon dioxide and hydrogen generation. Furthermore, the initial high concentration of sulphate in the leachate is slowly reduced as the redox potential drops. The generated sulphide may also precipitate iron, manganese and heavy metals that were dissolved in the initial stages of this phase (Christensen and Kjeldsen 1989).

Phase III is the second intermediate anaerobic degradation stage in which methanogenic bacteria slowly start to appear. The sulphate-reducing bacteria are also included in the anaerobic decomposition process since this group of bacteria in many ways resembles the methanogenic group, and sulphate is a major compound of many waste types. The sulphate-reducing bacteria are obligate anaerobes and may convert hydrogen, acetic acid and higher volatile fatty acids during sulphate reduction. However, this group is more likely to oxidize organic compounds to carbon dioxide. Therefore, if the activity of sulphate reducers is high, less organic material is available for methane production.

As the methane gas increases, hydrogen, carbon dioxide and volatile fatty acid concentrations decrease. The conversion of fatty acids causes the pH within the landfill to increase. This subsequently reduces the solubility of calcium, iron, manganese and heavy metals in the leachate, which are then precipitated as sulphides.

Phase IV is characterized by the steady production of methane gas. During this phase, methane gas constitutes approximately 50 to 60% (by volume) of the gas composition. The high rate of methane gas formation maintains low concentrations of volatile acids and hydrogen, and as a result the leachate is able to sustain a neutral pH.

Phase V represents the stage in which recalcitrant wastes is decomposed. This phase involves low methane production, constant pH levels in the leachate and low leachate strength. Nitrogen starts to appear again at this stage in the landfill gas due to diffusion from the atmosphere because of the low methane gas production rate. The last stage is domi-
nated by the obligate anaerobic methanogenic bacteria, which produce methane and require very low redox potentials. Two groups of bacteria comprise the methanogenic group: the hydrogenophilic and the acetohilic bacteria. The hydrogenophilic bacteria convert primarily acetic acid to methane and carbon dioxide.

This idealized waste degradation sequence assumes that the waste is homogeneous and of constant age. A realistic landfill occupying waste cells with highly variable age and composition may yield a somewhat different overall picture (Barlaz et al. 1989b).

Nozhevnikova et al. (1993) were able to show that in small landfills methane that is produced in the anaerobic zone can be oxidized completely in the upper fill layers. This ability of biogas extraction is important not only as an additional energy source, but also as controlling the environmental problems associated with methane and its release to the atmosphere. Through the usage of geophysical, isotopic and microbiological techniques, Nozhevnikova et al. (1993) were able to provide detailed descriptions and confirmations of processes occurring in landfill sites. Overall, it was concluded that in the upper fill layer, methane became heavier and carbon dioxide lighter due to the microbiological oxidation processes. The occurrence of methanogenesis was observed in the upper part of the anaerobic zone where the organic substance concentration was relatively high (Nozhevnikova et al. 1993).

Governing Abiotic Factors

The major abiotic factors in a landfill that can affect methane gas production include the concentration of oxygen, pH/alkalinity, sulphate, nutrients and inhibitors as well as temperature and water content (Campbell 1993; Christensen and Kjeldsen 1989; Doedens and Cord-Landwehr 1989). These factors alone may not be critical, but they may, however, influence other parameters which control MSW degradation process rates and activities. A brief description of the abiotic factors follows.

**Oxygen**

Methanogenic bacteria are particularly sensitive to the presence of oxygen. Extensive gas recovery pumping may create a substantial vacuum in the landfill, forcing air into the landfill. This would extend the aerobic zone in the landfilled waste and eventually prevent formation of methane in these layers. However, under normal conditions, aerobic bacteria in the top of the landfill will cause solid waste to readily consume the oxygen and limit the aerobic zone to less than 1 m of compacted waste (Christensen and Kjeldsen 1989).

**pH**

Methanogenic bacteria exist best within a narrow pH range of 6 to 8. If the activity of methanogenic bacteria is low, for some reason, their conversion of hydrogen and acetic acid decreases. This causes the hydrogen
pressure to build up, and at elevated pressures, acetogenic bacteria cannot convert volatile fatty acids, particularly butyric and propionic acid. The accumulation of these acids consequently lowers the pH within the landfill, and eventually stops methane production. The methanogenic system in the landfill is rather delicate, and balanced relations between the various bacterial groups are crucial for a good rate of methane production. A buffer material, such as demolition waste or soil, could be added to the landfill so that appropriate pH levels are maintained.

**Sulphate**

It was reported that in both batch experiments and laboratory landfill simulations, methane generation was dramatically reduced in the presence of high sulphate concentration within the landfill environment (Campbell 1993). This reduction is not related to any toxic effects of sulphate on methanogenic bacteria but rather due to substrate competition.

**Nutrients**

Microorganisms that participate in the anaerobic degradation of waste require nutrients such as sulphur, calcium, magnesium, potassium, iron, zinc, copper, cobalt, molybdate, selenium and, in particular, nitrogen and phosphorus. These nutrients are found in most landfills. However, insufficient homogenization of the waste may result in nutrient-limited environment. It was reported that the optimal ratios between organic matter (expressed as chemical oxygen demand), nitrogen and phosphorus are listed as 100:0.44:0.08 (Christensen and Kjeldsen 1989; Stegmann and Spendlin 1989). In cases where there is a limited nutrient for anaerobic degradation, phosphorus would be the most likely element.

**Inhibitors**

In addition to the inhibitory effects of oxygen, hydrogen, proton activity, and sulphate, it has been suspected that carbon dioxide, salt ions, sulphide, heavy metals and specific compounds are potential inhibitors of methane production. It was reported that at carbon dioxide partial pressures between 0.2 to 1.0 atm, the conversion of acetic acid decreases (Cossu et al. 1993; Christensen and Kjeldsen 1989). Cations such as sodium, potassium, calcium, magnesium and ammonium have been observed to stimulate anaerobic decomposition at low concentration while inhibit it at high concentrations.

**Temperature**

It was documented that the rate of methane generation increased significantly (up to 100 times) when the temperature was raised from 20 to 40°C in laboratory simulations (Christensen and Kjeldsen 1989). Furthermore, it was indicated that in a deep landfill with a moderate water flux, landfill temperatures of 30 to 45°C can be expected, even for temperate climates. This was attributed to the heat flux from the landfill
to the surroundings being low due to the insulating effect of the waste; the heat is also generated by the anaerobic decomposition process, which may result in a temperature rise within the landfill environment.

**Moisture content**

The availability of moisture content of about 25 to 60% has shown to exponentially increase methane gas production (Mata-Alvarez and Mertinez-Viturtia 1986; Ham and Bookter 1982). The benefits of increased water content in a landfill include limiting oxygen transport from the atmosphere, facilitating exchange of substrate, nutrients, buffer, dilution of inhibitors and spreading of microorganisms within the landfill.

**Methods of Enhancing Degradation**

**Leachate Recirculation**

Leachate recirculation refers to the collection of leachate discharged from a landfill, and redistributing it through the waste to enhance biodegradation and reduce the contaminant concentrations in the leachate. Several studies have been conducted to investigate the effects of leachate recirculation (McCreanor and Reinhart 1996; Reinhart 1996; Reinhart and Al-Yousifi 1996; Townsend 1996; Morelli 1992; Pohland 1980) on MSW biodegradation.

Pohland (1980) investigated leachate recycling with two simulated landfill cells. Each cell was filled with about 3 m of shredded MSW and allowed to reach its field capacity through natural rainfall. One cell was then left open to simulate open landfill conditions and the other was sealed to enable landfill gas measurements and to prohibit water evaporation. Tap water was added to the sealed cell in an amount equivalent to that of rainwater received by the open cell. The temperature ranges within the two cells were not observed to differ significantly (Pohland 1980). The pilot study indicated a decline in leachate contaminant concentration with daily recirculation of leachate. This observation was attributed to the biological stabilization of readily available organic components contained within the cell. It was noted that the daily recirculation of the leachate provided the microorganisms with sufficient nutrients and, as a result, overall conversion of the waste was enhanced. Also, it was observed that the volatile acid concentrations in the leachate rose sharply, and that was followed by fermentation of these acids to produce carbon dioxide and methane. Furthermore, it was observed that a reduction of biological oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC) and volatile acids to produce carbon dioxide and methane had occurred at a faster rate in the sealed cell than in the open cell (Pohland 1980). This observation was attributed to the positive exclusion of oxygen which is detrimental to methanogenic bacteria.

Doedens and Cord-Landwehr (1989) performed a more detailed
study of leachate recirculation. The investigation was conducted on three scales: test cells and active landfill sections, both containing leachate recycling as well as on a large-scale landfill equipped with recycling techniques. The purpose of the test cell experiment was to investigate the degree of stabilization achieved with leachate recirculation. Four test cells were used, each consisting of an air tight, temperature-regulated steel cylinder containing compacted shredded waste with an original water content of 24 to 31%.

Test Cell 1 was supplied with 660 mm/year of rainwater, and all the leachate that was released was recycled back into the cell. The remaining three test cells originally contained 50% of the year’s precipitation with various water compositions. No leachate recycling was carried out in Test Cell 2, which only received rainwater as well. Test Cell 3 was irrigated with a combination of rainwater and leachate. Test Cell 4 was brought to a saturation point with the leachate from a stabilized landfill — in other words, to the point where the daily amount of water entering the cell equalled approximately the amount discharging from the cell.

Test Cell 1, with leachate recirculation, showed the highest decrease in COD concentration in the leachate during the examination period of 300 days. Test Cell 3 showed the lowest loads of COD, BOD, Cl, Zn and Pb in the leachate. In Test Cell 1, with leachate recirculation but with twice the amount of rainwater, the concentration of organics decreased faster, but the leachate contained about twice the amount of contamination in comparison with Test Cell 3. The amount of contaminants in the leachate of Test Cell 2, which had comparable conditions but without leachate recirculation, was two to three times as high as that of Test Cell 3.

The methane gas production rate observed in the test cells was used as a measure of the waste stabilization. It is evident that Test Cell 2, which received no leachate recirculation, exhibited the highest gas production. This result leads to the conclusion that leachate recirculation did not enhance the stabilization of the solid waste. Leachate recirculation did, however, stimulate a rapid decrease of COD and BOD concentrations in the leachate.

Barlaz et al. (1989b) and Leushner (1989) also found that leachate recirculation without nutrient addition is ineffective in enhancing methane production or improving leachate quality because of low pH levels. They noted, however, that recycling leachate enhanced microbial activity by providing better contact between insoluble substrates, soluble nutrients and the microorganisms, which resulted in leachate COD and total volatile acids concentration decrease, once methane production became established.

In various laboratory studies, leachate recycling enhanced the decomposition of waste and improved leachate quality when a variety of materials, such as buffers, nutrients and microbial inoculum, were added to the leachate and recirculated through the solid waste (Bogner 1990; Barlez et al. 1989b; Leushner 1989; Mata-Alvarez and Martinez-Viturtia 1986; Stegmann 1983).
The above studies all agreed that buffering the leachate being recycled enhanced decomposition by allowing the proper pH to be established. It was found that once a neutral pH, ranging from 6.8 to 7.4, was reached, rapid methane production commenced. Typical buffers include caustic and calcium carbonates.

It was observed by Stegmann (1983) and Leushner (1989) that the addition of nutrients such as nitrogen and phosphorus, and buffers to the recycled leachate significantly shortened the initial phase of degradation, and methane generation commenced earlier. However, the continued addition of nutrients after methane production had started did not improve the methane production rate above what was experienced through buffer addition alone. Furthermore, it was found by Barlaz et al. (1989b) and Leushner (1989) that anaerobically digested sludge was an excellent source of microbial inoculum. When leachate was recycled with buffer, nutrients and sludge, the rate of methane production was substantially higher than with all the other cases and, therefore, achieved the fastest rate of waste stabilization.

The effect of variable rates of leachate recirculation on solid waste stabilization and leachate generation rates was examined by Al-Yousifi and Pohland (1993). Recirculation rates of 25 to 100% of the total leachate generated were employed in the simulations. They found that the higher the leachate recycling rate, the greater the quantity of methane gas produced. This observation is related to the higher quantities of organic substance made available during high leachate recirculation. However, higher leachate recirculation rates resulted in longer lag times before methane generation began.

It was suggested in many studies that the leachate recycle rates and frequencies during the early acetogenic phase initially be low and then gradually increased as methanogenesis becomes established (Pohland and Al-Yousifi 1994; Cossu et al. 1993; Farquhar 1989; Pohland 1980; Pohland 1975). Also, it was recommended that total quantities of accumulated leachate should be restricted to the amount needed to effectively operate the landfill system as a bioreactor, and to minimize the eventual quantity requiring ultimate disposal, with or without post treatment after stabilization of the landfill had been achieved (Pohland and Al-Yousifi 1994; Ham 1993; Bookter and Ham 1982; Pohland 1975).

In a study to determine the reduction potential of PCB-contaminated sediments in an anaerobic bioreactor system, Pagano et al. (1995) also used the leachate recycle method. Landfill leachate was used to provide a carbon, nutrient, and/or microbial source. There was significant reduction in the total chlorine/biphenyl of the original Aroclor sediments in the laboratory-scale bioreactor system. In terms of PCB dechlorination in sediments, the detoxification is attributed to methanogenic conditions. An innovative in-line sampler was validated and utilized to measure the current internal status of the bioreactor system. When applying this technique to large-scale landfill sites, it was found by the researchers that degradation of PCB-contaminated sediments was inhibited or did not
occur because of engineering designs, which create dry and sterile environments. In order to effectively promote degradation of contaminants in landfills, it was concluded that there must be adequate moisture also available (Pagano et al. 1995).

Size of Waste Particles

The well-mixed, shredded refuse permits greater contact between the key constituents required for methane production: moisture, substrate and microorganisms. Thus, a smaller particle size could increase the rate of the hydrolysis of the organic waste. However, Barlaz et al. (1990 and 1989b) reported that refuse with 250- to 350-mm particle sizes produced 32% more methane after 90 days than refuse with 100- to 150-mm particle sizes. The reason for this outcome is that further stimulation by a reduced particle size may have caused too rapid a rate of hydrolysis, resulting in an accumulation of acidic end products and a lower pH. The acidic conditions then limit methane production.

Sludge Addition

Municipal sewage sludge can be added to MSW as a source of microorganisms and as a source of nitrogen and phosphorus as well as other nutrients. Typically, these sludges were anaerobically digested, but not dewatered. The contents of septic tank bottoms and animal manures have also been recommended (Barlaz et al. 1990).

As fresh refuse begins to decompose, there is an imbalance between the fermentative and methanogenic organisms, leading to a decrease in the pH of the system (Townsend et al. 1996). The use of sludge balances activities of the two types of bacteria and prevents the initial pH decrease. Rapid refuse decomposition has been observed in test lysimeters when municipal sludges were added (Barlaz et al. 1990).

Occasionally, there is an increase in carboxylic acid production due to the sludge addition. Thus, often a buffer is added in conjunction with the sludge. The buffer maintains the pH of the refuse ecosystem near neutral, allowing the methanogenic bacteria in the sludge to acclimatize to the refuse system more quickly than in the absence of a buffer. The addition of sludge and buffer has been successful in promoting the onset of methane production from fresh refuse.

Another inoculum for fresh refuse is old refuse. Methanogenesis can be stimulated by adding old, anaerobically degraded refuse, as the waste acts as a dilutant against the accumulation of toxic compounds. The addition of old refuse has been proven to be a very effective enhancement technique (Barlaz et al. 1990).

To improve the conditions for methane production, sludge and composted MSW were added to shredded fresh MSW (Doedens and Cord-Landwehr 1989). The sludge was anaerobically digested but not dewatered, and the old MSW was composted for 1 to 2 months. The ratio of MSW solids to sludge solids was 7:1 on a dry weight basis. A positive
effect due to the use of composted MSW was noted by Doedens and Cord-Landwehr (1989). Methane gas production was noted to be highest when MSW was mixed with composted MSW (Stegmann and Spendlin 1989). Also, it was noted that the BOD concentration rapidly decreased when composted MSW was added; additions of inorganic material and sawdust to shredded MSW enhanced gas production; and addition of food waste resulted in an inhibition of methane gas production (Stegmann 1983).

From the above studies, it can be concluded that high concentration of organic acids due to the introduction of food waste inhibit methane production. In other words, the acidic environment prevents growth of methanogenic populations. The addition of inert material dilutes the organic acids, thereby reducing the organic acid to solids ratio. It was also found that the BOD concentration of the leachate decreased dramatically when stable methane production took place. However, the organic content of the leachate may still be high even when gas production is at a maximum because the gas production is not stable. It comes into question whether or not organic leachate concentration can be used as an indicator for gas production and composition.

Lift Design

The usual practice in modern sanitary landfill operation is to place waste in highly compacted 2 to 3 m lifts, with or without daily cover. It has been found that MSW compacted at a low density in thin layers without daily cover produces high strength leachate over short periods of time (Stegmann 1983). Also it was reported that refuse built up in 2-m lifts degrades slower than in 1.3-m lifts. The COD concentration of leachate was found to be a function of solid waste lift thickness (Ham and Bookter 1982). In addition, the period of the elevated COD levels was longer in deeper waste lifts. It was concluded that the lift thickness is an important factor which affects the leachate composition (Ham and Bookter 1982). In landfill cells, where a second lift was added to a lift that had been in place for 5 years, the leachate data showed no major changes in organic composition. It was determined that the lower lift was able to attenuate the leachate from the higher lift (Stegmann 1983).

Daily cover has an adverse effect on enhancement of biological degradation. Experiments by Ham and Bookter (1982) showed that the application of soil cover dramatically increased the period during which COD concentrations were high. The leachate had a high organic content for the first 3 to 4 years after placement. Cells that were not covered reached high COD concentrations quickly, followed by a rapid stabilization of waste in which COD values were maintained at low levels. The time required to reach these low levels was less than a year. Covering the refuse prolonged the period of elevated leachate COD values.

Methane concentration is increased and methane production is delayed by the presence of soil cover (Ham and Bookter 1982). The landfill cover not only reduces the flow of decomposition gases out of the landfill and prevents oxygen from entering, but it also affects the decom-
position processes within the landfill. There were, however, serious aesthetic problems associated with uncovered cells, especially at high ambient temperatures.

Another important factor in the design of lifts is that anaerobic decomposition mainly occurs in the bottom layers of the landfill. Studies have shown that once COD concentrations in the leachate reach low levels, they remain so even while waste is landfilled on top. An experiment conducted by Stegmann (1983) showed that leachate was anaerobically treated in the bottom layer of a lysimeter. First, the leachate COD concentration was allowed to decrease to low levels in a lysimeter with one layer of waste. Then, a second lift was placed on top and samples of the leachate in between the two layers were withdrawn for analysis. High COD concentrations were found between the two lifts, but by the time the leachate flowed through the bottom waste layer, the leachate COD concentration decreased to the same low values as previously measured. The leachate was treated anaerobically in the bottom layer of the lysimeter (Stegmann 1983).

It was also found by Ham and Bookter (1982) that partially decomposed refuse has the ability to attenuate leachate. They found that the COD concentration in the leachate was reduced by 75% after passing through the lower lift when no soil cover was used. The COD was reduced by 99% when a soil cover was placed in between lifts. This is probably due to attenuation by the cover soil.

In column tests performed by Stegmann (1983), it was estimated that at 30°C, 1 kg of BOD can be treated by percolating through 1 ton of anaerobically decomposed MSW. At 10 to 15°C, 0.01 kg BOD was treated by 1 ton of dry MSW.

Based on the current state-of-the-art, the lifts should be designed to incorporate leachate treatment layers consisting of old waste. Landfills should be constructed in thin lifts, and a cover should not be used immediately. The first lift could be designed such that the polluted leachate from higher lifts is treated by the first layer. The first layer should be uncompacted so readily degradable organics can decompose aerobically and are allowed to stabilize before addition of subsequent lifts. Modification of landfilling practices as suggested above could result in an 85 to 90% reduction in COD production per unit weight of MSW (Ham and Bookter 1982).

**Moisture Content Management**

It was indicated by Barlaz et al. (1990) that moisture stimulates growth of anaerobic microorganisms since it was observed that total anaerobic populations in a landfill were larger near the water table. A higher moisture content also stimulates methane production. In field-scale tests, methane was not detected for two years in refuse that had a moisture content at field capacity (45.2%). However, when the water content was increased to 60%, methane was detected in six months. Studies show that the moisture content is one of the most critical variables con-
trolling gas production (Barlaz et al. 1990). It was reported by Christensen and Kjeldsen (1989) that there is an exponential increase in gas production rates between 25 and 60% moisture content.

In a landfill, the lack of opportunity for contact between microorganisms, substrate and growth factors limits biodegradation. As the moisture content increases, opportunity for contact increases. Therefore, adjusting the water content to field capacity initially or providing a continuous flow of water through the refuse accelerates decomposition.

High moisture contents stimulate the hydrolysis, but an accelerated rate of hydrolysis can be inhibitory. At high waste densities, each particle is in closer contact. Thus, for the same moisture content, there is more water in contact with the particles. As solid waste density increases, therefore, the optimum moisture content decreases.

A study conducted by Stegmann (1983) used two laboratory lysimeters, each filled with shredded MSW mixed with industrial wastes. There was no water addition in one lysimeter, and the other was maintained at a 65% moisture content. There was no leachate recirculation in both lysimeters. Methane was not produced in the first lysimeter until after a year due to high organic acid concentrations, which resulted in low pH levels. The acidic conditions inhibited growth of methane-producing bacteria, and as a consequence waste did not decompose. It was found that by adding water, a portion of the organic acid can be removed by the leachate and methane production can occur (Stegmann 1983).

**Temperature**

According to Barlaz et al. (1990), greater than 90% of the methane potential of municipal refuse can be attributed to the cellulose/hemicellulose action. Therefore one must understand the parameters limiting the degradation of these polymers to CO₂ and CH₄. Through the interactions of various microbial populations such as sulphate-reducing bacteria (SRB) and/or methanogens, cellulose catabolism is mediated. The sulphate-reducing bacteria activity allows a reduction in the redox potential, which creates a suitable reducing environment for methanogens to function. These two microorganisms also compete for the same substrate (acetate and H₂) (Watson-Craik et al. 1994).

In an experiment conducted by Watson-Craik et al. (1994), a multistage continuous culture model system was used to separate the physiological groups of the isolated association without the loss of overlap of their association. Thus, individual species were studied without disturbing the association. The multistage continuous culture systems were inoculated with cellobiose and butyrate-degrading methanogenic microbial associations enriched from fresh (one month old) shredded refuse obtained from Wilderness Landfill Site. After carbon sources were selected (cellobiose and butyrate), association establishment and stabilization, the different temperature parameters were studied (mesophilic and thermophilic ranges). Temperature is a very important factor because of the varying ranges found in such a heterogeneous landfill. The direct effect of
temperature on microbial activity could be manipulated to optimize methane production. Thus, it is necessary to realize the temperature constraints on individual microorganism in order to control the methanogenic fermentation.

The optimum temperature range for methanogenesis was generally found to be from 30 to 35°C (Watson-Craik et al. 1994). Due to further increase in temperature (45 to 55°C), methanogenic populations were inhibited. Furthermore, it was concluded that prolonged exposure to these temperatures may result in an unbalanced fermentation or the redirection of electron flow in the presence of exogenous sulphate to thermophilic propionate-utilizing SRB. It was suggested that a refuse emplacement strategy be employed to control the temperature.

**Enzyme Addition**

Laegervist and Chen (1993) have experimented with the addition of cellulolytic enzymes under methanogenic and acidogenic conditions using 0.1 m³ landfill models. Enhanced degradation was observed following enzyme addition. The conversion of volatile solids was approximately 40 to 50% for both methanogenic and acidogenic conditions.

Cellulolytic enzymes were used because the major component of the degradable municipal solid waste is cellulose, and by manipulating the enzyme activity, it is possible to control and enhance the hydrolysis of cellulose. Laegervist and Chen (1993) examined enzyme effects in acidogenic, methanogenic and the semi-aerobic environments. The study, however, was only concerned with the acid and methanogenic conditions of the landfill. In the experiment, four models were used: two for methanogenic models (1, 2) and the other two (3, 4) for acidogenic models. Leachate recycle and temperature maintenance at 30°C was maintained throughout all four models. Laegervist and Chen (1993) concluded that the increased acid production generated by the enzyme addition during intense methane production was not sufficient to suppress the subsequent methanogenesis that occurred. This was explained by the nature and content of the waste and its non-homogeneous distribution. Enzyme addition during the decline of gas production did not cause an increase in the production rate of gas (Lagerkvist and Chen 1993).

**Landfill Model Application**

As mentioned before, it is beneficial to minimize the time period in which degradation occurs in order to reduce gas emissions after the landfill is closed, to ease the requirements of leachate treatment, and to be successful in reclaiming the landfill site. The main objective of a study done by Wall and Zeiss (1995) was to test the ability of biological enhancement to reduce the time to reach stabilization and to determine the effects of biodegradation on settlement. In order to conduct this study, six landfill test cells were constructed to model both settlement and decomposition
over extended periods of time. Of the six, three acted as model bioreactor landfills and the others as secure vaults. All six were monitored for gas composition (CO₂ and CH₄) and volume, leachate pH and TOC as well as refuse settlement. The following conditions were exposed to cells 1 and 3 to enhance biodegradation: temperature maintained at 25°C, refuse initially saturated with distilled water, approximately 50 litres, leachate recycle on a weekly basis, and buffer (Na₂CO₃ and K₂CO₃) and anaerobically digested sewage sludge addition. For the dry-vault system, temperature was maintained at 4°C and no additional moisture or microbial seed was added to inhibit waste degradation. Results of this study suggested that test cells could effectively model actual landfill behaviour. Wall and Zeiss (1995) indicated that biodegradation and settlement occur in three distinct stages: initial compression (settlement that occurs directly when an external load is applied to a landfill), primary compression (compaction due to the dissipation of pore water and gas from the void spaces), and secondary compression (due to creep of the refuse skeleton and biological decay).

When studying the relationship of microbial mass and activity in the biodegradation of waste, Murphy et al. (1995) were able to draw interesting conclusions under aerobic conditions. The municipal solid waste was incubated in lysimeters with moisture content controlled with recycled leachate. Both anaerobic and aerobic conditions were studied. The data revealed that aeration resulted in increased biomass production and greater cellulolytic activity. The aerobic inground digester included leachate recirculation in order to provide optimum moisture. Various parameters were assessed, including bacterial biomass and number counts by adenosine triphosphate analysis, acridine orange counts, viability, adenylate energy charge and cellulose activity. The results determined the following advantages (Murphy et al. 1995): (1) increased degradation speed and completeness, (2) elimination of costly leachate buffering systems employed in anaerobic operations, (3) no need for gas collection as methane and hydrogen sulphide production would be eliminated, and (4) aeration that allows reduced odour problems and accelerate degradation of cellulose in landfills.

Field Applications

Leachate recirculation is the most common enhancement mechanism used in the field. The U.S. EPA reported that more than 200 landfills use leachate recirculation as a means of leachate management (Reinhart 1993). Some of the problems that limit acceptance of this method in the field include excessive head on the bottom liner, clogging of liner drainage systems, and leachate breakouts. Full-scale research and development will help identify proper operating procedures to avoid some of these problems.

The effectiveness of leachate recirculation is highly dependent on the technique chosen to distribute the leachate. Some of these methods include prewetting of waste, spraying, surface ponds, vertical injection
wells, and horizontal infiltration devices.

Experimental study was conducted on full-scale test cells at the Mountain View Controlled Landfill project, CA, to investigate the effect of various enhancement techniques (Pacey 1989). One cell contained additional water, a calcium carbonate buffer, recycled leachate, and sewage sludge. Another cell was identical to the first cell, but did not use leachate recirculation. Another cell contained buffer and sludge, with recirculation, but no additional water. A fourth cell had a buffer and the fifth had added sludge, both of them with additional water. There was also a control cell. After more than 4 years, the remaining methane producing potential of each cell was measured. The cell with the greatest remaining methane producing potential (57%) was the cell with only buffer and additional water, and the cell with the least potential (17%) was the first cell which incorporated all the enhancement techniques, including additional water, buffer, sludge and recirculation. This proves the effectiveness of the techniques in stimulating gas production, as the cell with the highest remaining methane producing potential is the cell which exhibited the least degradation.

Results from the Seamer Carr Landfill in the UK indicated that a 40% reduction in COD concentrations occurred within 20 months of the initiation of leachate spraying, compared to leachate from an area where leachate recirculation was not employed (Reinhart and Carson 1993). Leachate recirculation was also found to be beneficial in other full-scale landfills: the Owens-Corning Landfill in Ohio, the Central Solid Waste Management Centre Landfill in Delaware, Central Facility Landfill, Worcester County, Maryland, and the Southwest Landfill in Alachua County, FL (Reinhart and Carson 1993; Reinhart 1996).

Large-scale experiments were performed at the Bornhausen Landfill in Goslar, Germany (Doedens and Cord-Landwehr 1989). Three test cells were constructed in thin layers with and without covering and recirculation. The results found no increase in the organic content of the leachate after 350 to 450 days of leachate recirculation. The thin layer construction technique proved to be more effective than the leachate recirculation process. The cover, with an additional water dosage under the lining system, did not improve leachate quality, but did minimize the volume of leachate that required treatment.

Another two test sites at Bornhausen were constructed, one with recirculation, and the other without. The time period for stabilization was twice as long for the site without recirculation than the site which used leachate recirculation. This study also found that recirculating leachate over old landfill reactors in which stabilized leachate was already produced resulted in BOD reductions of 90 to 99% (Doedens and Cord-Landwehr 1989).

The effects of leachate recycling on landfill stabilization were investigated by Townsend et al. (1996) on a full-scale landfill in north-central Florida. The leachate recycling system was constructed and operated on a section of the composite lined landfill. An infiltration pond leachate recy-
Cling system was used to recirculate the leachate to the landfill. Samples of leachate, landfill gas and landfilled solid waste were collected and analysed throughout a 4-year period (1988–1992), before and after the start of leachate recycling (Townsend et al. 1996). The subsidence of the landfilled waste was also measured in wetted and dry areas of the landfill. During the 4-year period, the lined section of the landfill received approximately 300 tons of waste per day. This study indicated that, in general, leachate recycling did not improve the quality of the leachate. Measurements of pH, total dissolved solids, COD, BOD and ammonia of the leachate were performed over the 4-year period. Leachate recycling reduced the pH of the leachate from levels above neutral to levels below neutral. However, the drop in pH was not low enough to inhibit microbial activity. COD and BOD concentrations in the leachate reached levels similar to those before leachate recycling was implemented. Leachate TDS and ammonia increased somewhat over the period before and after leachate recycling began (Townsend et al. 1996).

The study by Townsend et al. (1996) also reported the conditions for waste stabilization present in areas with and without leachate recycle. This was proven through measurements of methane gas in the landfill, waste temperature and pH of the leachate. In areas where leachate was recirculated, the moisture content of the landfilled waste was significantly increased. Furthermore, measurements of landfill subsidence and biochemical methane potential of the waste indicated that the degree of stabilization was greater in areas where the leachate recycling occurred.

The issue of daily cover was addressed in the Seamer Carr Landfill study (Reinhart and Carson 1993). The low permeability cover that was located between higher permeability waste lifts caused horizontal movement and leachate ponding. This problem was compounded when large volumes of leachate were recirculated. Leachate accumulations of 1.2-m depths were reported due to the use of daily cover. This same problem was also discovered at the Lycoming County Landfill, PA, where clays and silty soils were used for daily cover (Reinhart and Carson 1993). To alleviate these problems, daily cover should be minimized or avoided, or soils of high permeability should be used.

Aspects of lift design were tested in a full-scale landfill at Lingen, West Germany (Stegmann 1983). In one cell, refuse was compacted in several 0.5 to 1 m lifts. The second cell contained waste 1 m high without compaction. After 6 months, another lift, 1 m in height, was placed on top of this first lift in the same manner. Above this, waste was continually placed in compacted 2-m lifts. Both cells employed leachate recirculation. The BOD leachate concentration was significantly lower in the cell with the uncompacted lift. In addition, the COD concentration was 2000 mg/L in the cells with the uncompacted initial lifts, while the COD was ten times higher in the cell which contained strictly the compacted lifts. It was therefore advantageous to provide uncompacted layers in this case.

Efforts can be made to reduce the time for aerobic decomposition in the first layer. When the aerobic Rottedeponie Landfill in Germany was
converted to a highly compacted anaerobic operation, the BOD concentra-
tions of the leachate remained at the low levels which were present during
aerobic conditions (Stegmann and Spendlin 1989). Refuse should be placed
in thin layers (0.2–0.3 m) over large areas. This results in higher leachate
production rates, but leachate concentrations are expected to decrease ear-
lier. Since large areas of the waste are in contact with the atmosphere, aer-
obic processes take place to a certain degree and thus reduce the readily
degradable organic fractions. Also, moisture distribution is much more
even. The study also examined the effect of the lift thickness on the
leachate organic content. It was noted that the BOD and COD concentra-
tions are significantly higher for the deeper solid waste lifts.

One unique landfill design in the UK involved using air injection
through vertical gas wells into completed landfills to promote aerobic
degradation. The aerobic metabolism processes that were stimulated raised
the temperature of the landfill and promoted anaerobic activity, as evi-
denced by the increase in methane production (Reinhart and Carson 1993).

Many researchers have found the importance of studying microbio-
logical processes within landfills. There was also a need to establish a
method to assess the degree of decomposition of waste within a site or the
energetic potential of any landfill site. The work of Attal et al. (1992) and
Iza et al. (1992) developed a procedure to accurately estimate the degree
of decomposition of waste in a site which would cover the complete mass
of the waste. The final objective was to obtain sufficient data to define a
procedure capable of determining the energetic potential of any landfill
site (Attal et al. 1992).

The degree of decomposition was based on a biochemical methane
potential test and various gases were monitored, including CO₂, H₂ and
N₂. The quantity of biogas was calculated from the volume and composi-
tion of the gaseous phase. Waste was sorted and stored at 4°C, until calci-
nation at 550°C. Organic matter was estimated by the volatile suspended
solid percentage (% VSS). The samples were then diluted and purged
with N₂, and finally sealed and incubated at 55°C (Attal et al. 1992).

Many conclusions were drawn from the the results of the study con-
ducted by Attal et al. (1992). The size of the particles of waste was an
important factor. This study chose 25 to 30 kg having an acceptable 20%
error; however, other studies vary from 50 kg to several tons. Another fac-
tor was location within the landfill — the heterogeneous nature of the
municipal solid waste had to be accounted for. This study relied on the
fact that materials of the same age are in horizontal layers and waste is
disposed homogeneously in each layer. Temperature (50°C) at 10 m and
below indicated active anaerobic biological decomposition under ther-
mophilic conditions. Methane levels detected indicated that it increased
with depth. The low proportion of methane observed in the upper layer
suggested that it must be in the hydrolysis acidification phase. Biological
parameters such as % VSS and methane potential were also observed.
Percent VSS decreased as depth increased. It was found that the longer
the waste burned the greater the mineralization. For example, at 25m the
waste was completely mineralized. Also the older the waste, the lower methane potential. In conclusion, the biodegradable potential of the waste increased as organic matter content increased (Attal et al. 1992). The overall advantage of the sampling technique and technical procedure developed by Attal et al. (1992) showed the validity of studying anaerobic degradation of MSW in landfills. With the possibility of changing sample sizes, it allowed for the heterogeneous nature of various landfill sites. It also revealed that within a landfill there is a regular structure — a number of layers with its own homogeneous waste of different ages (Attal et al. 1992).

Summary and Conclusion

Stabilization of solid waste in sanitary landfills is dominated by biological processes. Several techniques to enhance biological degradation and to reduce leachate production have been presented. Laboratory-scale studies indicate that recycling leachate alone reduces the organic content in the leachate, but does not enhance waste stabilization. However, by adding buffer, nutrients and municipal sludge to the leachate being recirculated, not only was waste degradation enhanced, but leachate quality was also improved.

In terms of enhancement by reducing the size of waste particles, studies have found that the smaller size particles increase the rate of hydrolysis up to a minimum waste size. Degradation of waste particles smaller than the minimum size resulted in a decreased methane production.

High moisture contents stimulate methane gas production. By increasing the moisture content above the field capacity of the waste, the rate of gas production is increased.

Temperature also has an important role in biodegradation. The optimum temperature for methanogenesis based on model studies show 30 to 35°C to be advantageous.

By adding anaerobically digested sewage sludge to MSW as a microbial and nutrient source, refuse decomposition can be enhanced. The combination of sludge and buffer also promotes the onset of methane production when added to fresh MSW.

Methanogenesis is stimulated by the addition of old, partially degraded MSW to fresh refuse. When leachate percolates through layers of degraded MSW, the concentration of organics reduces significantly.

The design of waste lifts in landfills was found to have an effect on the degradation rates of organic materials. Deep lifts resulted in high COD concentrations in the leachate. Daily cover had a negative effect on gas production and leachate quality. It was suggested that landfills constructed with thin lifts and cover be placed after a short stabilization period. The placement of uncompacted layers of old MSW at the bottom of a new landfill should be considered as means of leachate treatment.
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